NONLINEARLY MODULATED DIGITAL MICROACTUATORS FOR NANO-PRECISION DIGITAL MOTION GENERATION

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ABSTRACT

This paper presents a nonlinearly modulated digital actuator (NMDA) for producing nano-precision digital stroke. The NMDA, composed of a digital microactuator and a nonlinear micromechanical modulator, purifies the stroke of the digital actuator in order to generate the high-precision displacement output required for nano-positioning devices. The function and concept of the nonlinear micromechanical modulator are equivalent to those of the nonlinear electrical limiters, such as Zener diodes. We design and fabricate both linear and nonlinear modulators, having an identical input and output strokes of 15.2µm and 5.4µm, respectively. We compare the characteristics of the linear and nonlinear modulators linked to an identical digital actuators. The NMDA shows the repeatability of 12.3±2.9nm, superior to that of 27.8±2.9nm achieved by the linearly modulated digital actuator (LMDA). We experimentally verify the displacement purifying capability of the nonlinear mechanical modulator, applicable to nano-precision positioning devices and systems.

INTRODUCTION

Nano-precision actuators are required to manipulate and control a new class of microenergy information media [1-4], such as photons and biofluids. Recently, micromechanical converters [5,6] have been suggested for high-precision positioning applications based on the linear mechanical modulation immune to electrical noise. Ultimate precision of the micromechanical converters [5,6], however, has been constrained by the precision of the digital actuation. Displacement stroke of the digital actuators contains an inherent uncertainty in the order of ±0.1µm, generated by the micromachining errors and the sidewall roughness/slopes of mechanical stoppers. In this work, we propose NMDA (Fig.1) having a built-in nonlinear micromechanical modulator for reducing the displacement error of the digital microactuator, thereby producing a purified high-precision motion stroke.

Figure 2 illustrates a simple model of the micromechanical modulator, composed of a pair of mechanical spring-mass set. As shown in the modulation curve of Fig.3a, the linear modulator having two linear springs may reduce the magnitude of errors, but it cannot reduce the error-to-displacement ratio (i.e., the noise-to-signal ratio). On the other hand, the nonlinear modulator (Fig.2), composed of a nonlinear spring (k_2) and a linear spring (k_1), reduces the magnitude of errors as well as the relative error using the slope change of the nonlinear modulation curve (Fig.3b).

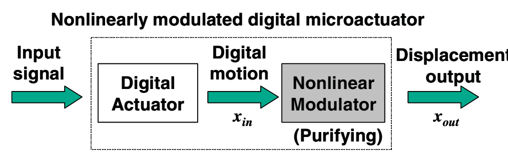


Fig.1 Configuration of the nonlinearly modulated digital microactuator (NMDA).

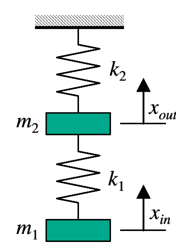


Fig.2 Model of the micromechanical modulator, composed of two springs, k_1 and k_2.

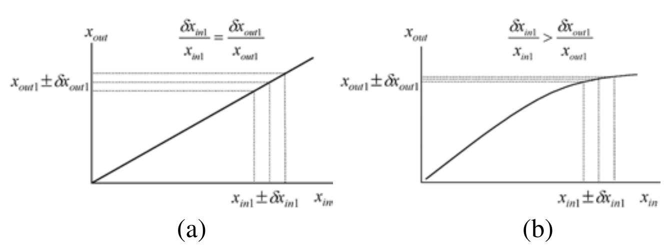


Fig.3 Displacement modulation curves, x_{in}-x_{out}, of the micromechanical modulators: (a) linear modulator; (b) nonlinear modulator.

THEORETICAL ANALYSIS AND DESIGN

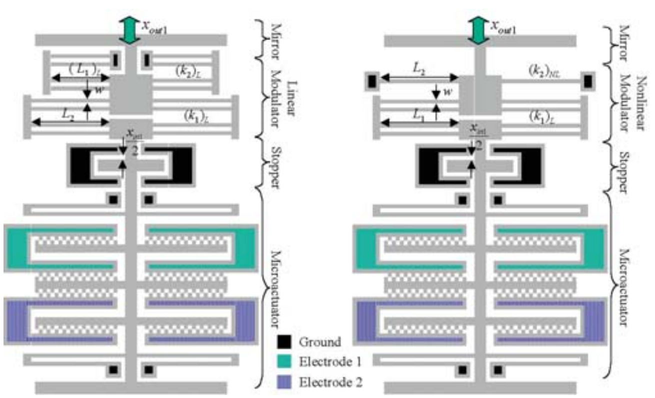
We have designed two kinds of prototypes, (Fig.4, Table 1) where identical digital microactuators are attached to the linear and nonlinear micromechanical modulators. Microactuators provide the digital motion (x_{in}) of 15.2µm to the input port of the micromechanical modulators (m_1 in Fig.2) using motion-limiting function of the mechanical stoppers.

Micromechanical modulators utilize the folded beams and the fixed-fixed beams as the linear and nonlinear springs, respectively. For a large deflection, the fixed-fixed beam becomes stiff because of stretching effects. The folded beam, however, releases the axial stretching by allowing the shift of folded structure. From finite element analysis, the fixed-fixed beam has the variable stiffness of 1.11~4.16N/m in the beam deflection range of 0~2.7µm. The input-output relations of the linear and nonlinear modulators can be calculated from the simple model of Fig.2, as follows.

$$(x_{out})_L = \frac{(k_1)_L}{(k_1)_L + (k_2)_L} x_{in} \qquad (1)$$

$$(x_{out})_{NL} = \frac{(k_1)_L}{(k_1)_L + \left\{\int (k_2)_{NL}\, dx\right\} \Big/ x_{out}} x_{in} \qquad (2)$$

where $(k_1)_L$ and $(k_2)_L$ are the constant stiffness of the linear springs 1 and 2 and $(k_2)_{NL}$ is the variable stiffness of the nonlinear spring 2. Using the finite element method and Eqs. (1) and (2), we obtain the displacement modulation curves (Fig.5) of the linear and nonlinear modulators, having an identical input and output pair of 15.2µm and 5.4µm.



(a) (b)

Fig.4 Schematic view of the mechanically modulated digital microactuators using two different modulators: (a) linear modulator; (b) nonlinear modulator.

Table 1. Measured dimensions of the fabricated devices.

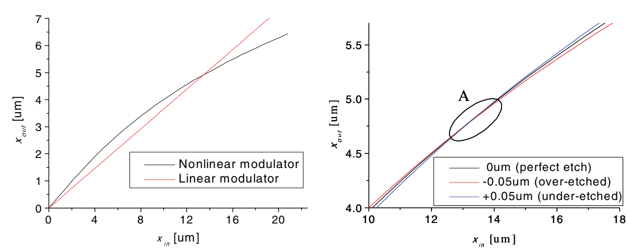
Structure thickness		t	40 µm
Beam width		w	2.4 µm
Length of beam 1		L_1	500 µm
Length of beam 2	Linear modulator	$(L_2)_L$	416 µm
	Nonlinear modulator	$(L_2)_{NL}$	500 µm
Digital input displacement		x_{in1}	15.2 µm
Proof mass 1		m_1	13.5 µg
Proof mass 2		m_2	2.53 µg
Stiffness of spring 1		k_1	1.11 N/m
Stiffness of spring 2	Linear modulator	$(k_2)_L$	1.93 N/m
	Nonlinear modulator	$(k_2)_{NL}$	1.11~4.16 N/m

To evaluate the precision of the actuation, we defined the repeatability as the double of the standard deviation in the repeated actuation. When the input displacement with the error (repeatability : δx_{in}) is applied to the micromechanical modulator, the repeatability of the modulated output (δx_{out}) is:

$$\delta x_{out} = \frac{d\,x_{out}}{d\,x_{in}} \cdot \delta x_{in} \qquad (3)$$

where (dx_{out}/dx_{in}) is the slope of the modulation curve. In the case of a digital actuator fabricated by deep RIE (Reactive Ion Etching) process, the repeatability (δx_{in}) is about 70.7nm, due to the sidewall roughness of the mechanical stoppers in the order of ±0.05µm. We can calculate the repeatability of the linearly and nonlinearly modulated outputs (δx_{out}) as 25.8nm and 15.4nm, respectively.

Additionally, we have examined the variation of the modulated outputs in the LMDA and NMDA, when the whole device has been under- or over- etched. In the portion A of Fig.5b, we find that NMDA also maintains stable displacement output against the over-etching and under-etching of the micromechanical beam springs and micromechanical stoppers.



(a) (b)

Fig.5 Displacement modulation curves of the linear and nonlinear micromechanical modulators: (a) overall curves; (b) Nonlinear modulation curves depending on the microfabrication error of ±0.05µm.

FABRICATION PROCESS

Figure 6 shows the one-mask fabrication process for two different prototypes. The prototypes were defined by the deep RIE (Reactive Ion Etching) of the top silicon layer of SOI (Silicon On Insulator) wafer. Figures 7 and 8 show the fabricated linearly and nonlinearly modulated microactuators, respectively.

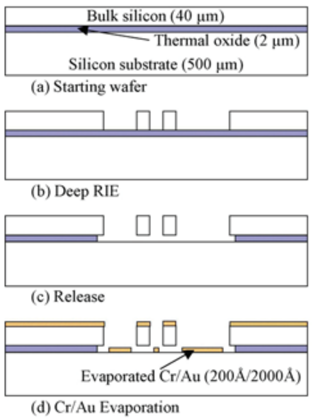
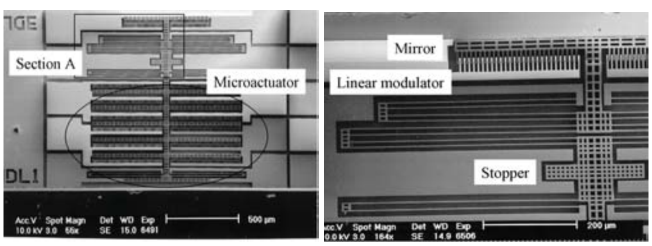
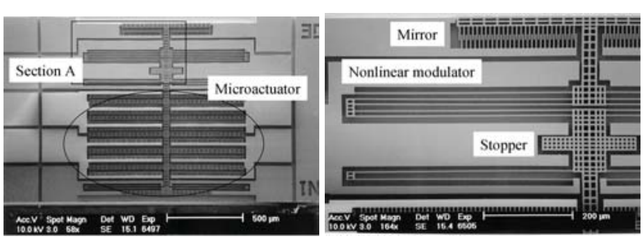


Fig.6 Microfabrication process of the mechanically modulated microactuators.



(a) (b)

Fig.7 SEM photographs of the linearly modulated microactuator: (a) overall structure; (b) an enlarged view of the Section A in (a).

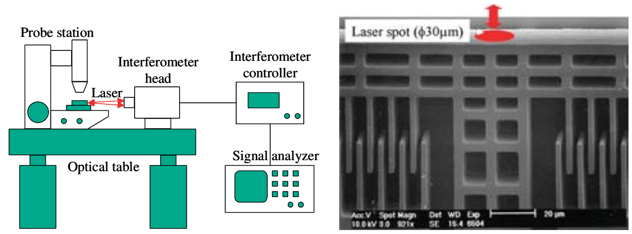


(a) (b)

Fig.8 SEM photographs of the nonlinearly modulated microactuator: (a) overall structure; (b) an enlarged view of the Section A in (a).

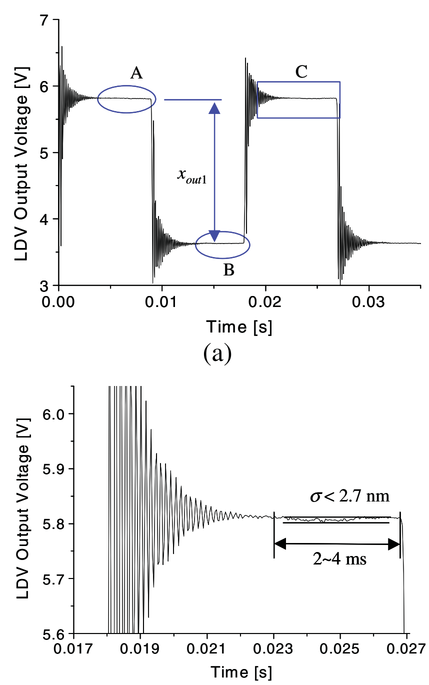
EXPERIMENTAL RESULTS

We experimentally demonstrate the feasibility of the NMDA that produces a purified motion stroke required for nano-precision positioning devices. For a nano-precision measurement, we use the modified Mach-Zehnder interferometer (Fig.9a), where laser beam has been focused on the micromirror (Fig.9b) attached to the modulated output port. The fabricated LMDA and NMDA are actuated digitally by applying two out-of-phase square wave signals of 60Hz, 25V to the electrodes 1 and 2 of Fig.4. Figure 10 shows the interferometer output signals for the mirror displacement. The modulated displacement (x_{out}) has been measured from the distance between two stable portions (A and B in Fig.10a). The measurement uncertainty of the modulated displacement output is 7.6nm, due to the signal jitter (Fig.10b) having a standard deviation of 2.7nm.



(a) (b)

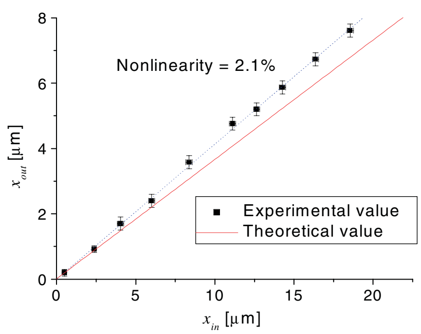
Fig.9 Modulated displacement output measurement: (a) experimental apparatus; (b) laser spot on the vertical mirror.



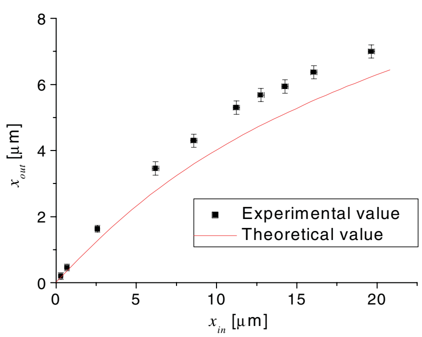
(b)

Fig.10 Modulated displacement output measurement: (a) displacement output signal; (b) an enlarged view of the portion C in (a).

Figure 11 compares the measured and estimated modulation curves of the fabricated micromechanical modulators for varying displacement input. The experimental values of the linear modulation curve are drawn as a linear line with the nonlinearlity of 2.1% and those of the nonlinear modulation curve coincides well with the theoretical nonlinear curve. For the precision evaluation, we have performed repeated output measurements (7 times) from the linearly and nonlinearly modulated digital microactuators, both producing the output in the range of 5.46±0.10µm. Experimental values of the repeatability in Table 2 have been obtained from the double of the standard deviation in the repeated measurement. Table 2 demonstrates that NMDA produces the digital motion stroke with the repeatability of 12.3±2.9nm, superior to that of 27.8±2.9nm achieved by the LMDA. Figure 11 and Table 2 demonstrate experimentally that the NMDA improves the repeatability of the modulated output, compare to the conventional LMDA.



(a)



(b)

Fig.11 Displacement modulation curves of the linear and nonlinear micromechanical modulators: (a) linear modulator; (b) nonlinear modulator.

Table 2. Experimental and theoretical values of the repeatability in the modulated displacement output of the linearly and nonlinearly modulated digital microactuators.

Prototype	Device #	Experimental	Theoretical
LMDA	1	25.2±2.9 nm	25.8 nm
	2	32.6±2.9 nm	
	3	25.6±2.9 nm	
NMDA	1	11.6±2.9 nm	15.4 nm
	2	11.0±2.9 nm	
	3	13.0±2.9 nm	
	4	13.4±2.9 nm	

CONCLUSIONS

We presented the nonlinearly modulated digital microactuator (NMDA) and the experimental verification of its capability for producing a high-precision digital stroke. We designed and fabricated the conventional linear and proposed nonlinear modulators, connected to the digital microactuators, which had an identical input and output pair of 15.2µm and 5.4µm. From the experimental study, the measured linear and nonlinear modulation curves coincided well with the theoretically estimated curves. In precision evaluation using the measured repeatability, the NMDA showed the repeatability of 12.3±2.9nm, superior to that of 27.8±2.9nm achieved by the linearly modulated digital microactuator (LMDA). We experimentally demonstrated the capability of NMDA for producing a high-precision digital stroke, and showed its potential for nano-precision input purifying devices.

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